Selecting a clear-sky model to accurately map solar radiation from satellite images

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Selecting a clear-sky model to accurately map solar radiation from satellite images

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ABSTRACT: The HelioClim project aims at mapping solar radiation over a wide area that covers Europe, Africa, and Atlantic Ocean. To achieve this purpose, Meteosat images will be processed with the Heliosat method, which turns images into maps of solar radiation at ground level. One of the inputs of this method is the solar radiation under clear sky. The quality of the estimations strongly depends on the accuracy of the radiative transfer model under clear sky. Therefore several clear-sky models are assessed in this paper. It is found that taking into account the turbidity of the atmosphere, the Linke turbidity factor, T_L(AM2), provides better results. The models using T_L(AM2) are then compared. Among them, the « ESRA model », set up in the course of the realisation of the 4th edition of the European Solar Radiation Atlas, fits better than the others. Accordingly, this model is chosen to be used in the Heliosat method.

1 INTRODUCTION

Satellite methods offer an alternative to interpolations of punctual ground measurements, allowing thus to study continuously wide areas. This advantage is well exploited in this study, that only uses satellite images to map solar radiation.

Indeed, the purpose of the HelioClim project, carried out in Ecole des Mines de Paris, is to establish a climatological database of solar radiation over an area as wide as Europe, Africa, and Atlantic Ocean, during the past fourteen years. To achieve such a project, satellite images, especially Meteosat images, will be processed with the Heliosat method, world-wide used.

The original version of the Heliosat method (Cano *et al.*, 1982) has been modified for the HelioClim project, but the principle is still the same.

This method makes use of the digital count of Meteosat images to derive a cloud index, which characterises the transmittance of the atmosphere over the pixel under concern. The atmospheric clearness index is then computed from this cloud index, finally providing global solar radiation.

In order to accurately compute solar radiation, the Heliosat method requires a good radiative transfer model under clear skies. This point is discussed in this paper, where different clear-sky models are first described and then compared.

2 RADIATIVE TRANSFER MODELS UNDER CLEAR SKIES

Radiative transfer models under clear skies give the value of the solar radiation received at ground level in clear-sky conditions.

For some models, the global radiation is split into the beam and the diffuse components, allowing thus a finer description of the radiative transfer.

The inputs are varying from a model to another: the simplest models just take into account the solar elevation, while more detailed ones may include other inputs such as aerosols, water vapour, ozone, elevation of the site, barometric pressure, temperature, or ground albedo, in order to better model the atmospheric transmittance.

The value of clear-sky radiation is needed in the process of the Heliosat method, and the assessment of the solar radiation at ground level from satellite images strongly depends on the accuracy of the radiative transfer model used.

For that reason, we investigate several clear-sky models and study their relevance for the assessment of solar radiation from satellite images.

3 DESCRIPTION OF VARIOUS CLEAR-SKY MODELS

3.1 *Models with solar elevation as unique input*

The first model presented here is the clear-sky model of the WMO (World Meteorological Organization) document 557 (1981, page 120). This model, only acceptable for stations at low altitudes (less than 400 meters), gives the following expression for the global horizontal irradiance under cloudless skies:

$$G_{c(WMO)} = 0.95\, I_0\, \varepsilon\, (\sin \gamma_S) / (1 + 0.2 \operatorname{cosec} \gamma_S) \qquad (1)$$

where:
I_0, the solar constant, is equal to 1367 $W.m^{-2}$;
ε is the correction used to allow for the variation of sun-earth distance from its mean value;
γ_s is the solar altitude angle. γ_s is equal to 0° at sunrise and sunset.

The original version of the Heliosat method (Cano *et al.*, 1986) used the model of Bourges (1979) to compute the global irradiance under clear-sky:

$$G_{c\,(Bourges)} = 0.70\, I_0\, \varepsilon\, (\sin \gamma_S)^{1.15} \qquad (2)$$

Later, Moussu *et al.* (1989) used the model of Perrin de Brichambaut and Vauge (1982), hereafter noted PdBV, which has the same inputs as the previous models. This one provides larger values than the model of Bourges and is given by:

$$G_{c\,(PdBV)} = 0.81\, I_0\, \varepsilon\, (\sin \gamma_S)^{1.15} \qquad (3)$$

These models are very easy to implement. However they do not take into account parameters that influence solar radiation, such as ground albedo or atmospheric turbidity (aerosols, water content, ...) and accordingly yields rough evaluations.

3.2 *Clear-sky models with more inputs*

Other models have more inputs representing the properties of the atmosphere, thus reducing the overall inaccuracy.

The first one is the other clear-sky model proposed in the WMO document 557 (1981, page 124), which uses as another input the atmospheric turbidity. The horizontal global irradiance under clear-sky is given by the following equation:

$$G_{c(WMO)2} = \varepsilon\, (1297 - 57\, T_L)\, \sin \gamma_S^{(36+TL(AM2))/33} \qquad (4)$$

where $T_L(AM2)$ is the Linke turbidity factor for an air mass equal to 2. We recall that $T_L(AM2)$ is a function of the optical path for aerosols and water vapour, and that it characterises the transmittance of the blue sky. A value of 1 stands for a dry and clean atmosphere. This WMO model is still simple but it is stated that it is suitable particularly if the solar elevation is higher than 20°-30°.

The other clear-sky models split the global radiation into a beam and a diffuse components. Among them, three clear-sky models have the same equation for the beam radiation: the model of Dumortier (1995), a model developed at the University of Oldenburg (Beyer *et al.*, 1997) based on calculations made using radiative transfer code MODTRAN 3.5 (Kneizys *et al.*, 1996), called the MODTRAN model, and the model developed within the European Solar Radiation Atlas, hereafter noted the ESRA model.

For these models, the horizontal beam radiation under cloudless skies is given by the following equation:

$$B_c = I_0\, \varepsilon\, \sin\gamma_s\, \exp\!\left(-0.8662\, T_L(AM2)\, m\, \delta_R(m)\right) \qquad (5)$$

where:
m is the relative optical air mass;
δ_R (m) is the integral Rayleigh optical thickness.
The quantity :

$$\exp\!\left(-0.8662\, T_L(AM2)\, m\, \delta_R(m)\right) \qquad (6)$$

represents the beam transmittance of the beam radiation under cloudless skies. The relative optical air mass m expresses the ratio of the optical path length of the solar beam through the atmosphere to the optical path through a standard atmosphere at sea level with the sun at the zenith. As the solar altitude decreases, the relative optical path length increases. The relative optical path length also decreases with increasing station height above the sea level, z. A correction procedure is applied, obtained as the ratio of mean atmospheric pressure, p, at the site elevation, to mean atmospheric pressure at sea level, p_0. This correction is particularly important in mountainous areas. The relative optical air mass has no unit; it is given by Kasten and Young (1989), where γ_s^{true} is in degrees:

$$m(\gamma_s^{true}) = \frac{(p/p_0)}{\sin\gamma_s^{true} + 0.50572(\gamma_s^{true} + 6.07995)^{-1.6364}} \qquad (7)$$

with the station height correction given by:

$$p/p_0 = \exp(-z/z_h) \qquad (8)$$

where z is the site elevation, z_h is the scale height of the Rayleigh atmosphere near the Earth surface, equal to 8434.5 meters, and γ_s^{true} is the solar altitude angle corrected for refraction.

All the variation of the beam transmittance with air mass is included in the product m δ_R (m). Figure 1 displays the beam irradiance for $p=p_0$ (sea level), and for different values of turbidity factor ($T_L(AM2)$ = 2, 3, 5, 7), as a function of solar elevation.

For the three models, the diffuse irradiance also depends on the Linke turbidity factor. The higher the turbidity, the greater the absorption and scattering of

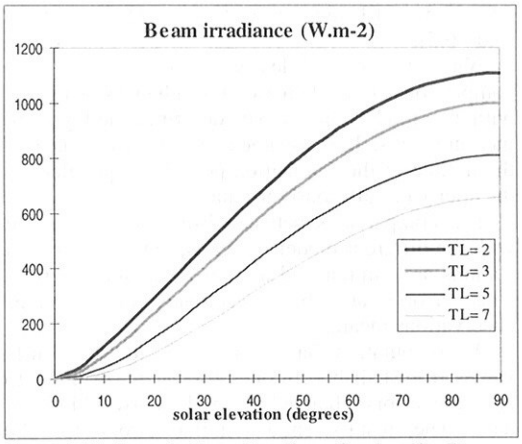

Figure 1. The beam horizontal irradiance for clear sky, B_c.

the solar radiation by the atmosphere, and therefore the higher the diffuse component and the smaller the beam component.

The expressions for the diffuse components are given below.

The diffuse component of the model of Dumortier (1995) is the following:

$$D_c = I_0\, \varepsilon\, (0.0065 + (-0.045 + 0.0646\, T_L) \sin \gamma_S - (-0.014 + 0.0327\, T_L) \sin^2 \gamma_S \tag{9}$$

with the conditions:

$\gamma_S < 70°$

$2{,}5 \leq T_L \leq 6{,}5$

The MODTRAN model gives the following expression for the diffuse component:

$$D_c = I_0\, \varepsilon\, (a + b\, T_L + c\, T_L^2 + (d + e\, T_L + f\, T_L^2) \sin \gamma_S + (g + h\, T_L + i\, T_L^2) \sin^2 \gamma_S \tag{10}$$

$a = 0.017991$	$d = -0.112593$	$g = -0.019104$
$b = -0.003967$	$e = 0.101826$	$h = -0.022103$
$c = 0.000203$	$f = -0.006220$	$i = 0.003107$

For the ESRA model, the diffuse irradiance is defined as the product of the diffuse transmission at zenith, T_{rd}, and a diffuse angular function, F_d, as following:

$$D_c = I_0\, \varepsilon\, T_{rd}\left(T_L(AM2)\right) F_d\left(\gamma_s, T_L(AM2)\right) \tag{11}$$

with the following diffuse transmission at zenith ($\gamma_S = 90°$):

$$T_{rd}(T_L(AM2)) = -1.5843.10^{-2} + 3.0543.10^{-2}\, T_L(AM2) + 3.797.10^{-4}\, [T_L(AM2)]^2 \tag{12}$$

and the following diffuse angular function:

$$F_d\left(\gamma_s, T_L(AM2)\right) = A_0 + A_1 \sin(\gamma_s) + A_2\left[\sin(\gamma_s)\right]^2 \tag{13}$$

The coefficients A_0, A_1 and A_2, only depend on the Linke turbidity factor. They are unitless and are given by:

$$\begin{cases} A_0 = 2.6463\,10^{-1} - 6.1581\,10^{-2}\, T_L(AM2) + 3.1408\,10^{-3}\left[T_L(AM2)\right]^2 \\ A_1 = 2.0402 + 1.8945\,10^{-2}\, T_L(AM2) - 1.1161\,10^{-2}\left[T_L(AM2)\right]^2 \\ A_2 = -1.3025 + 3.9231\,10^{-2}\, T_L(AM2) + 8.5079\,10^{-3}\left[T_L(AM2)\right]^2 \end{cases} \tag{14}$$

with a condition on A_0:

$$if\left(A_0.T_{rd}\right) < 2.10^{-3}, \quad A_0 = 2.10^{-3}/T_{rd} \tag{15}$$

This condition is required because A_0 yielded negative values for $T_L(AM2)>6$. It was therefore decided to impose this limiting condition to achieve acceptable values at sunrise and sunset.

The diffuse irradiance is represented in figures 2 and 3 for the Dumortier, MODTRAN, and ESRA models for different values of the Linke turbidity factor ($T_L(AM2) = 2$ and $T_L(AM2) = 7$).

Finally, from the previous equations of beam and diffuse irradiances, the horizontal global irradiance under clear-sky for the three models can be deduced from:

$$G_c = B_c + D_c \tag{16}$$

Other models such those described by Perez (1987) or by Iqbal (1983), which not only take into

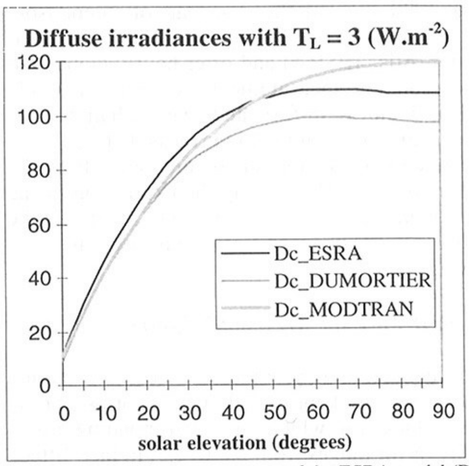

Figure 2. The diffuse components of the ESRA model (D_c ESRA), the DUMORTIER model (D_c Dumortier), and the MODTRAN model (D_c MODTRAN) for $T_L = 3$ at mean sun-earth distance.

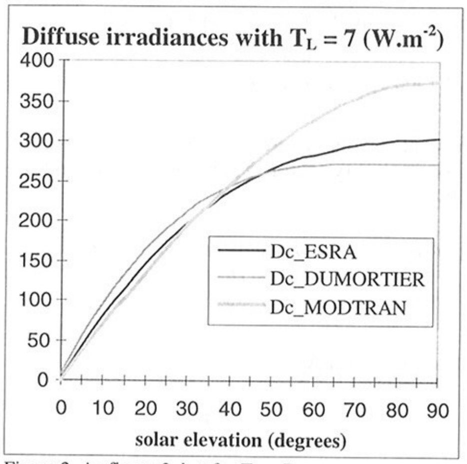

Figure 3. As figure 2, but for $T_L = 7$.

account turbidity, but also other parameters such as ground albedo, ozone, or water vapour, require data that are not always available. In the framework of the HelioClim project, which aims at mapping operationally solar radiation, such models cannot be included. Therefore we are not describing such models in this study. Anyway, some basic comparisons are reported below.

4 COMPARISON BETWEEN DIFFERENT CLEAR-SKY MODELS

The previous models have been analysed by comparison with ground data. The stations of the data set are located in Germany or in Belgium (see table 1). The period of measurement stretches from 1981 to 1990, offering thus ten years of comparison. This data set is extracted from the European Solar Radiation Atlas (ESRA) and offer hourly global and diffuse radiation measurements, except for Uccle (half-hourly global, diffuse, and beam radiations).

The diffuse, or beam component is deduced from the subtraction of the measured component from the global irradiation. Then, using the expression of the beam component given in equation (5), the Linke turbidity factor is deduced from the measurements as following:

$$T_L = - \ln(B_c / I_0\, \varepsilon \sin \gamma_S) / 0.8662\, \delta_R(m)\, m \qquad (17)$$

This computation provides a "clear-sky ground data set": only are kept measurements corresponding to clear skies, for which the corresponding Linke turbidity factor ranges from 2.0 to 6.5. In fact, fifteen intervals of T_L, partly overlapping each other, were used to distinguish clear from non clear skies: [2.0 - 3.5], [2.5 - 3.5], [3.0 - 3.5], [2.0 - 4.0], [2.5 - 4.0], [3.0 - 4.0], [2.0 - 5.0], [2.5 - 5.0], [3.0 - 5.0], [2.0 - 6.0], [2.5 - 6.0], [3.0 - 6.0], [2.0 - 6.5], [2.5 - 6.5], [3.0 - 6.5].

With this new "clear-sky ground data set", comparisons are made between irradiances estimated with the models previously described and ground measurements. It is assumed that the irradiance of the middle of the acquisition period is equivalent to the hourly or half-hourly irradiation.

The comparisons between irradiances estimated with the different models or measured at the ground stations are summarised as root mean square errors (rms errors) and bias (estimates mean minus observations mean).

A computation has been made to get hourly values from half-hourly ones for Uccle, in order to compare errors obtained from these two kinds of data. The results show similar errors for the assessment of the irradiation on hourly basis than those obtained from half-hourly basis.

4.1 *Comparisons of global radiations estimated from the model of Bourges, Perrin de Brichambaut & Vauge, and WMO*

The models described in section 3.1 have been compared with the clear-sky ground data set (table 1). Results (rms errors and bias) are shown in tables 2 and 3 for the ten years over all stations.

The estimations obtained with the model of Bourges present a high bias whatever the location and the Linke turbidity range. This model systematically under-estimates the clear-sky irradiation. Moreover the accuracy of this model remains poor. The rms error over the ten years ranges from 33 to 58 $Wh.m^{-2}$ for all locations and all T_L ranges. The model of Perrin de Brichambaut & Vauge gives higher radiation values, since the only difference between them is the multiplicative coefficient (0.81 for Perrin de Brichambaut & Vauge, 0.70 for Bourges). Consequently the under-estimation should be corrected. Indeed, the bias is reduced and is even positive indicating now an over-estimation. The rms error is generally lower than the model of Bourges, ranging from 17 to 57 $Wh.m^{-2}$ for the ten years, whatever the turbidity range and whatever the site. However, this model shows a high

Table 1. The data set of ground stations. Period of measurement: from January 1981 to December 1990.

Station Name	Latitude N ; Longitude E	Elevation
Braunschweig(Germany)	52.30 ; 10.45	83 m
Dresden (Germany)	51.12 ; 13.68	246 m
Hamburg (Germany)	53.65 ; 10.12	49 m
Trier (Germany)	49.75 ; 6.67	278 m
Würzburg (Germany)	49.77 ; 9.97	275 m
Weihenstephan (Germany)	48.40 ; 11.70	472 m
Uccle (Belgium)	50.80 ; 4.35	100 m

dependence on the range of T_L used: the higher the turbidities, the higher the errors. The rms errors ranges from 17 to 24 $Wh.m^{-2}$ for T_L between 2.0 and 3.5, and from 48 to 57 $Wh.m^{-2}$ for T_L between 3.0 and 6.5.

To check the validity of the model of PdBV, Moussu et al. (1989) compare it to the clear-sky model described by Iqbal (1983, model C) after the works of Bird and Hulstrom (1981 a, b) for various values of ground albedo, precipitable water thickness, and horizontal visibility. The comparison demonstrates that the shape of the model PdBV is consistent with the model C and that the variation of G_c is well described by the function $(\sin \gamma_S)^{0.15}$. However the magnitude of $G_{c\ (PdBV)}$ suffers from the lack of input parameters, as well as the model of Bourges.

Compared to those models, the first model proposed by WMO, given by equation (1), on the one hand gives lower bias than those obtained with the model of Bourges. On the other hand rms errors remain more stable than those noted with the PdBV model with a change in T_L range. However rms errors are ranging from 26 to 43 $Wh.m^{-2}$, and the overall accuracy remains poor, also suffering from a lack of inputs.

The results obtained with the second WMO model, see equation (4), are also given in tables 2 and 3. Taking into account the turbidity of the atmosphere really improves the accuracy: the values obtained with this model are close to the irradiances measured at the different stations: the rms error ranges from 16 to 29 $Wh.m^{-2}$ for all locations and all T_L ranges.

Table 2. Global clear-sky radiation in $Wh.m^{-2}$. Results obtained from the comparison between ground irradiations measured over all stations during ten years and the models of Bourges, Perrin de Brichambaut & Vauge, and WMO, for a T_L ranging between 2.5 and 3.5. The ground mean is equal to 328 $Wh.m^{-2}$.

	Bourges	PdBV	WMO1	WMO2
mean	290	336	303	333
rmse	53 (16 %)	20 (6 %)	34 (10 %)	20 (6 %)
bias	-38	8	-25	4

Table 3. As table 2 but for a T_L ranging between 2.5 and 6.5. The ground mean is equal to 363 $Wh.m^{-2}$.

	Bourges	PdBV	WMO1	WMO2
mean	348	402	373	361
rmse	42 (11 %)	51 (14 %)	39 (11 %)	25 (7 %)
bias	-15	40	10	-1

4.2 *Comparison of diffuse radiations estimated from the model of Dumortier, MODTRAN, ESRA, and WMO.*

In the previous section, some models have been tested, showing that the best results are obtained when taking into account the Linke turbidity factor. Another study (Rigollier *et al.*, 1999) investigated other models (Dumortier, MODTRAN, and ESRA) that take into account this Linke turbidity factor. Moreover, these models have another input: they depend on the elevation of the site. Some results of this study are reported below.

For those models, comparisons with ground data have also been made, using several large data sets including the present one. The expression of the beam radiation has been used to deduce the Linke turbidity factor and to choose clear skies data among all. Therefore only the diffuse component has been compared for the models of Dumortier, MODTRAN, and ESRA.

It was possible to investigate the influence of the geographical location on the estimations, since the stations are not only located in Europe, but also in Israel. The results are slightly the same for all sites, it is hence concluded that there is no influence of the ground elevation nor the geographical location on the quality of the estimations.

Moreover, the differences in error observed in 1994 between two remote sites such as Sede Boqer (Israel) and Vaulx-en-Velin (South France) are not higher than those observed between 1981 and 1990 for the different German stations. We conclude that the models are not affected by the climate.

The results computed over ten years show that even if the errors are similar for the three models, the ESRA model always gives the best results for all stations when considering average errors over the ten years. Being the most accurate and most robust model, the ESRA model is consequently recommended by Rigollier *et al.*

We have shown in the previous section that the second model presented in the WMO document (Eq. 4) provides good estimations of the global radiation. When comparing them to the results obtained with the ESRA model, a slight difference is noted, the model of ESRA being fairly more accurate: for the Linke turbidity factor ranging from 2.5 to 3.5 (respectively from 2.5 to 6.5), the rms error is equal to 22 $Wh.m^{-2}$ (resp. 17 $Wh.m^{-2}$), while the bias is -3 $Wh.m^{-2}$ (resp. -5 $Wh.m^{-2}$).

Tough this capability is not yet exploited, we feel that further improvements in the Heliosat method may request the knowledge of both the direct and diffuse components for clear skies. While the ESRA model clearly expresses both components, the WMO model presented in equation (4) only gives the global radiation under clear sky and does not have distinct beam and diffuse components. In fact, the WMO document 557 (1981, page 124) presents two distinct beam and diffuse components:

$$B_c = \sin \gamma_S \,[1390 - 31\, T_L(AM2)]\, \exp\,[-T_L/(12.6 \sin(\gamma_S+2))] \quad (18)$$

$$D_c = 383 \sin \gamma_S^{[(TL(AM2)+5.7)/30]}\, \exp[-4/T_L(AM2)] \quad (19)$$

We have compared the WMO beam radiation from equation (18) with that from ESRA for different Linke turbidity factors and solar elevations. This comparison shows that the beam components do not strongly differ.

In the study of Rigollier *et al.*, it has been proved that the ESRA model is accurate: rms errors were found to range from 11 to 35 $Wh.m^{-2}$ for all measurements (different years, different locations) and various Linke turbidity factors for diffuse irradiations up to 250 $Wh.m^{-2}$. But the comparison between the diffuse components from the WMO and ESRA models shows discrepancies between them, as shown in figure 4. These discrepancies are especially large with high values of Linke turbidity and demonstrate that the WMO model for diffuse component is not accurate enough. These findings proved true when comparing the WMO estimations with ground measurements: the rms error computed for the whole data set (all stations over ten years) for a Linke turbidity factor from 2.5 to 6.5 is equal to 33 $Wh.m^{-2}$ (with a ground mean of 113 $Wh.m^{-2}$) while the same error for the ESRA model is 22 $Wh.m^{-2}$.

Besides, as shown in figure 4, the diffuse WMO model does not behave correctly for low solar elevations. Indeed, for a Linke turbidity factor ranging from 2.5 to 6.5, and solar elevations from 5° to 10°, the WMO model widely overestimates the diffuse radiation: the bias over the seven stations of table 1 and during ten years is equal to 27 $Wh.m^{-2}$, while it is -1 $Wh.m^{-2}$ for ESRA. With the same conditions, the rms error is equal to 34 $Wh.m^{-2}$ and only 18 $Wh.m^{-2}$ for ESRA.

Considering these findings, the diffuse WMO model does not seem to be accurate nor commendable.

Moreover, regarding this WMO diffuse model, two strange facts have attracted our attention:

- Firstly, the values of WMO diffuse radiation computed with equation (19) do not agree with the table XII in page 124 of the same WMO document.
- Secondly, the values obtained while adding up both the beam and the diffuse components from equations (18) and (19), or the values given in table XII, differ from the values of global radiation computed with the equation (4).

Accordingly, we decide to select the ESRA model to compute solar radiation under clear sky. Including this model in the Heliosat method should improve the quality of the estimations of solar radiation from satellite images.

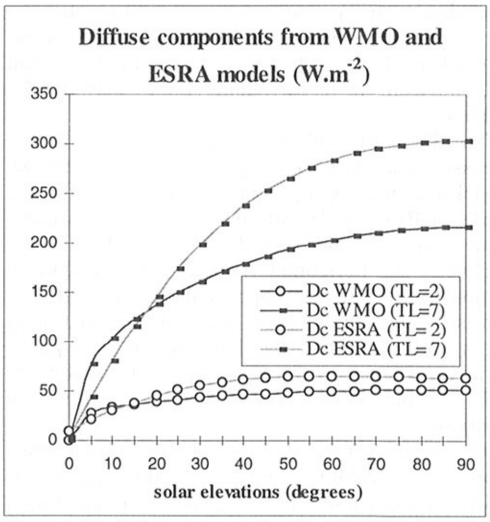

Figure 4. The diffuse components of the WMO (D_c WMO) and ESRA (D_c ESRA) models for Linke turbidity factors of 2 and 7.

5 CONCLUSION

Several clear-sky models have been presented and analysed for the estimation of clear-sky irradiance. The models need different data as inputs. The simplest ones only need the solar elevation, while more detailed ones take into account the transmittance of the atmosphere, by means of the Linke turbidity factor for example. Among them, some models need too many inputs, that cannot be acquired easily. Consequently they cannot be used in the framework of the HelioClim project and have not been studied here.

The purpose of the HelioClim project is to map accurately and operationally solar radiation from satellite images. The results obtained while taking into account the turbidity of the atmosphere are clearly better than the others. After a comparison between these models, that proposed by the European Solar Radiation Atlas (ESRA, 1999) proves to be the most accurate and most robust model as a whole, and is selected for the HelioClim project.

6 ACKNOWLEDGEMENTS

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